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PRELIMINARY STUDY ON LASER-DRIVEN FLYER-PLATE GENERATION FOR SHOCK INITIATION OF SECONDARY EXPLOSIVES

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EXECUTIVE SUMMARY

Laser initiation of energetic materials, particularly pyrotechnic materials, has been studied for a number of years. Recently there has been considerable work in developing techniques to initiate high explosives (HE's) using laser pulses. Laser initiation by shock wave generation in HE's has been attempted in three ways: (1) direct irradiation of the HE; (2) expansion of a high pressure plasma created by irradiation of a thin metallic film in contact with the HE; and (3) impact against the HE of a high velocity flyer plate launched by expansion of a high pressure plasma created by irradiation of a thin metal foil (laser-driven flyer plates).

Direct laser irradiation and laser irradiation of a thin film in contact with explosives have not yet demonstrated capability of reliably initiating HE's such as HNS, the acceptor explosive used in modern fuzes. However HNS has been successfully shock initiated with laser-driven flyer plates. Therefore, presently, the most promising approach to laser initiation of HE in a fuze is via laser-driven flyer plates.

Laser initiation has many advantages when compared to conventional initiation techniques. The principal ones are their immunity from stray electromagnetic fields, electrostatic discharges and stray electrical energy. Laser initiation can be used in all-electronic safety and arming devices (ESAD's) and also allows a great versatility in multiple point initiation systems by using optical fibers for energy transmission between the laser and initiation sites. But the cost, size and energy requirements of a suitable laser are too high for incorporation into all but the most expensive systems. It is considered that laser initiation is not a near term practical fusing option but will likely be within 8-10 years if sufficient resources are put into research and development.

The three laser initiation approaches are reviewed in this report but the emphasis is put on the laser-driven flyer plate technique. For the latter technique, it is concluded that there does not exist presently sufficient theoretical and experimental data to allow selection of the optimum design parameters of the laser detonator. Among the various experimental data, many were obtained under different and often incomparable conditions such that further extensive, targeted studies are still necessary to produce a suitable HE laser detonator. This report proposes a research plan on laser-driven flyer plates combining mathematical modeling with experimental work for studying all factors important to the efficient launching of the flyer plate. It also identifies the diagnostic techniques necessary to obtain a full understanding of the launching process.

This research contract provides DREV with a knowledge of the state of the art in laser initiation of HE materials. The proposed research plan gives the information that will allow DREV to decide whether or not to invest resources in laser initiation of HE materials.

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2. **Study of the physical processes** involved in the production of a flyer plate with a laser pulse influencing the acceleration process of the flyer, including radiation/target interaction with special consideration to the energy transfer in the process.

3. **Identification of the most promising designs of the slapper detonator.** Analysis of advantages and disadvantages of particular system will be performed.

4. **Identification of initial laser and material parameters** securing the best performance of the detonator (speed, size and shape).

5. **Identification of the initial experimental techniques** for plate launch.

6. **Selection of suitable diagnostic techniques** for plate launch.

7. ***Development of a research program*** **and report preparation.**

2. CRITICAL ANALYSIS OF AVAILABLE LITERATURE DATA

The National Optics Institute has computer access through two computer servers CANOLE and DIALOG to over 200 scientific databases. Several of these databases including INSPEC, NTIS, COMPENDEX (Engineering Index), PASCAL, CA SEARCH and AIAA were used for literature search related to this project. This chapter presents an overview of the literature related to the optically-induced initiation of explosion in secondary explosives.

2.1 Detonation mechanism in explosives

It seems that the detonation development mechanism in explosives is a well-understood process. The basic operational principle of all chemical explosives is the same. All chemical explosives have a common property consisting in that an exothermic chemical chain reaction with high heat production can be initiated in them under specific external conditions. As a result of this reaction, the explosive is converted into a mixture of hot gases which tend to expand rapidly. When confined, this expansion may generate enormous pressure on walls of the container, ultimately leading to its rapid destruction. In traditional, or primary, explosives, the chain chemical reaction can be easily initiated under normal pressure conditions when the local temperature of the explosive in some point exceeds a threshold value or when a relatively weak shock wave (generated by a simple mechanical impact typically caused by some kind of hammer, for example) is applied to the explosive. The local temperature increase can be created either by some external heat source or through conversion of kinetic energy into heat during impact of the explosive by a mechanical tool. Because of easy initiation of such explosives their handling is hazardous and this is a reason for search of safer explosives.

There exist some explosives, known as insensitive, secondary or High Explosives (shortly HE) which can be initiated only when the propagation speed of the reaction front exceeds some threshold value. Thus, normal deflagration or ordinary mechanical impact is usually insufficient to initiate their explosion. It is understandable that handling of such explosives is significantly safer and this is a reason why their application is rapidly expanding.

Local rise of temperature usually applied for initiation of ordinary explosive in so-called secondary explosives may lead to their burning but usually is not sufficient to initiate a rapid detonation process. Detonation processes in insensitive explosive can develop only when the density of the explosive

reaches some critical value. Because of their resistance to initiation, special means allowing generation of rapidly progressing reaction front are required. Two mechanisms of initiation of such explosives are recognized. One of them is Deflagration to Detonation Transition (DDT) while the second consists in direct generation of a strong shock wave in the explosive.

Initiation through the DDT process is possible only if deflagration is intense enough to create a rapid pressure build-up [1-3]. Practically, it can be achieved either by pressure build-up in a deflagration process when an explosive is ignited and burns under high-pressure conditions in a strong closed casting or when the required conditions are developed through local dynamic pressure and temperature build-up starting from a finite initial part. Rapid build-up of the pressure to the threshold value in the finite part of the explosive and follow-up transition to full detonation in the rest of the explosive is feasible in the DDT process under specific conditions [2], in some more sensitive explosives only, and to initiate less sensitive among them, more energetic methods are required. The feasibility of the first process was thoroughly studied a long time ago and it has been established that the ability to create a required build-up strongly depends on physical properties of the explosive, especially on its porosity.

Detailed study of the process conducted in many research centers lead to the conclusion that transition from deflagration to detonation is a complicated stage-wise process and the following four stages in the explosion growth from the hot spot of the reaction to the explosion were recognized [2]:

- deflagration,
- rapidly accelerating burning,
- low-velocity detonation (development speed 1000-2500 m/sec),
- normal detonation.

Normal detonation arises, as a rule, when burning proceeds from the ignited layer to the incompletely ignited explosive.

According to modern ideas [2,4], transition from deflagration to detonation of solid explosives can be represented by a general, very simplified schematic diagram (Fig. 1) and includes the following stages:

I - Stable layer by layer deflagration,

II - Convective burning,

III - Low velocity transition (800 - 3500 m/sec) by explosion when propagation velocity is usually a fraction of the sonic velocity in the original explosive (there is no consensus between researchers in the field regarding terminology of this stage so that the following terms are used: compressive burning, low-velocity detonation, wavelike burning, low-velocity stage),

IV - Steady-state normal detonation.

Each stage differs by the mechanism of heat transfer and initiation of reaction. The main form of heat transfer during layer by layer deflagration is molecular thermal conduction, while in convective burning it is forced convection. The low-velocity stage is initiated by compression waves while detonation is triggered by a shock wave. In general, development of the process accelerates from stage to stage. The final result of the development is the formation of a shock wave, which initiates detonation if its amplitude exceeds the critical value and if the system is able to detonate (the charge diameter is larger than the critical diameter of detonation). The existence and spatial extent of the individual stages depends on the structure of the charge, the physical and chemical properties of the explosive, and the experimental conditions. For instance, convective burning may pass directly to detonation by omitting stage III. The process may also terminate upon the establishment of the low-velocity stage with a constant velocity and the absence of detonation [2].

An excellent theory overview [4] of this process in porous, gas-permeable, reactive granular materials gives the following description of the process. First, the theory presumes that the process begins with ignition of a few grains by some external energy source. When the externally delivered energy is small, this process may end without detonation. If, however, this energy is larger than a given threshold value, conductive burning may accelerate and lead through all four stages to full detonation. The threshold value depends on explosive and even for the same explosive varies depending on various physical conditions including porosity, density and pre-loaded pressure, in particular.

In accordance with presently accepted theory, initially, the combustion process is slow and dominated by heat conduction within and between grains. At this stage generated hot product gases can penetrate into the pores of the unreacted material and, by preheating the grains, augment flame spread by several orders of magnitude above the deflagration rate driven by thermal conduction alone [5]. This mode of the flame spread can be self-accelerating and under conditions of strong confinement produce considerable gas pressures, which in turn leads to conditions favorable for detonation. Experimental study of the process [6] confirmed the existence of a convectively-driven flame front during flame spread in a column of HMX and showed that the onset of detonation was well removed from the location at which combustion began. Furthermore, this pre-detonation column length was shown to depend on the permeability of the granular bed. Further experimental studies have shown that considerable bed compaction occurs in the region ahead of the flame front. This, in turn, reduces the permeability of the granular bed and causes significant pressure buildup behind the flame front. This pressure further compresses the bed and accelerates the flame front. From these observations, it is evident that there is an important coupling of the thermal and mechanical processes associated with combustion, and that the mechanical processes are key factors in the formation of the shock wave and in achieving detonation. Once a shock

wave is formed, local "hot spots" release additional energy which enhances wave growth to detonation. There exist several possible mechanisms for this localized heating which are: microscale shock focusing during pore collapse, plastic work heating and intergranular friction at grains boundaries or in regions of high shear [7].

If explosive is ignited through the DDT, the speed of the process depends on explosive itself, its physical state (density, pressure, porosity), how fast initial energy is delivered, how this energy is distributed in the explosive, haw big is initiated volume, and other physical and chemical factors. Time and distance in the explosive required for full development of the detonation from deflagration is an important parameter characterizing explosive and applied method of initiation and these two parameters are often used as qualifying factors. It is obvious from the above presented theory that, because of its dependence on so many parameters, especially microstructure of the explosives which usually cannot be precisely controlled, repeatability of the DDT process has to be low. This reduces its usability in situations when precise timing is required, especially for simultaneous multipoint initiation. This is one of the most important factors enforcing development of alternative methods.

Further experiments [8] with imbedded diaphragm impermeable for gas have demonstrated that under similar conditions pre-detonation lengths in HMS explosive are practically the same as those for explosives without diaphragms. This suggests that mechanical load transfer from gas to solid phase plays an important role in DDT process and preheating may not be so important for proper development of detonation. The load transfer can occur either through the use of plugs in the flow such as diaphragms or by the drag forces acting on the grains during convective flow which cause compaction of the explosives which becomes impermeable and starts to act as a plug. At this moment it becomes evident that preheating of the explosives by the penetrating gas loses its importance and that at this stage the mechanical

load takes responsibility for further development of the detonation. The above suggests that creation of suitable mechanical load could lead directly to detonation bypassing all intermediate steps of DDT process. This creates physical background for direct initiation of the detonation by creation of strong shock wave in the explosives.

Thus, there exist two principal ways to initiate the secondary explosives either through DDT process or by generation of strong shock wave. Conditions for DDT initiation have been already shortly discussed above. The second method consists in generation of high strength shock wave directly in the explosive, able to create sufficient temperature and pressure build-up in front of the wave. In both cases build-up volume should be large enough to create self-propelling process expanding with supersonic speed. Initially, such wave was generated either using a small charge of primary explosive as a detonator or by fast ohmic evaporation of some material by a rapid discharge of a loaded capacitor through a narrow bridge in an electrical conducting line. The first method cancels safety gain obtained by application of the secondary explosives and will not be discussed here.

In this respect the second solution known as exploding bridgewire (EBW method) provides significant advantages and was primary used for their initiation. The method is based on a known fact that energetic electrical discharge through a narrow ohmic bridge may cause its evaporation creating rapidly expanding, high pressure plasma. When such bridge is immersed inside of an explosive, expanding plasma can generate strong shock wave sufficient for initiation of explosion. Its main disadvantage is a direct contact between the bridgewire and the explosive which may lead to their chemical interaction.

To secure physical separation of bridgewire and explosive another method was proposed. In this method the plasma created by rapidly evaporated bridge is used to launch a small, energetic particle of a solid material (usually called flyer) moving with very high velocity (up to several kilometers per second) in direction of the explosive. When it reaches the surface of the explosive, the strong shock wave is generated as a result of the impact. Because of the physical separation of the bridge from the explosive this solution becomes more popular. The devices based on this principle are known as slapper detonators had been specifically designated to initiate detonation in so-called secondary or high explosives (HE) and were described in the open literature for the first time in 1976 [9]. In both cases the timing of the electrical discharge through the exploding bridge (thus explosion time) can be electronically (even remotely) controlled, providing better handling security and better control over explosion time. The last method can be applied practically to all explosives, even these which cannot be initiated with any other methods.

The above solutions, however, have some disadvantages. One of them is sensitivity of the electronic devices to electromagnetic interference (EMI), which can be especially dangerous in case of nearby atomic explosion. The

synchronization of several detonators with precision required by some applications may also impose some difficulties due to the hardly controlled evaporation time of the conducting bridge. All these factors have created demand for alternative solution.

It seems that optics, especially lasers, may provide valued solution to some of the above discussed problems. In particular, many authors believe, that laser initiation of the explosive introduces an additional step into control chain of explosion which should additionally increase handling safety of the warheads and made them less prone to electromagnetic interference. It is also anticipated that division of a single laser pulse into many beams

separately delivered by optical fibers to required places can also solve synchronization problem and made such system resistant to the EMI. To prove these expectation intensive research has been undertaken in many countries. The present report contains a critical overview of this effort.

2.2 Laser initiation of the explosives

It seems that lasers can be used as a source of energy for all above mentioned methods and all explosives. In particular, easy to control, relatively low power semiconductor lasers can be used for direct inflammation of the primary explosives [10]. More powerful lamp-pumped solid state run-free lasers were used for initiation of the secondary explosives through the DDT process [11]. Finally, still more powerful Q-switched lasers are able to generate sufficiently strong shock wave in the explosive for direct initiation of the detonation in high explosives [11]. Physical mechanism involved in this kind of direct initiation, required power and energy are discussed in more details below.

Theoretical analysis of the laser ignition [12] leads to conclusion that there exists two distinct ranges of laser power density and pulse duration which may lead to initiation of high explosive. One of them concerns with thermal initiation of explosive through the DDT process, while the second one with impulse or shock initiation. Particular aspects of the laser initiation in these two situations are discussed below.

2.2.1 Thermal initiation of explosives with free-running pulse laser.

The thermal initiation is applicable only to explosives which can be initiated through DDT process and can be achieved with relatively low power laser beam interacting with explosives during relatively long time period. In this case two situation may appear. If power density is too low it may be insufficient to initiate any chemical reaction in the explosive at all. If power of laser beam is higher than some critical value, however, the fast ablation of explosive by laser beam may lead to burning hole through the explosive and in this way also to preclude the initiation of explosion. Minimal required power and the hole-through power differ from explosive to explosive, thus, for each explosive there exists some limited range of power density and pulse duration when thermal initiation is possible. When available power density is within the acceptable range, the laser beam initiates the burning of the explosive, which through the DDT process may enter the detonation stage [13,14]. The initiation time of explosion depends on attainable power density and decreases with increase of this value. As it was mentioned before porosity of the material is extremely important in achieving DDT phenomenon. Low porosity reduces free volume in the explosive, allowing the rapid pressure build-up. The laser initiation has significant advantages over pyrotechnic and EBW method. Even if the pyrotechnic igniter materials have a high theoretical energy density, during explosion it creates solid end products which consume significant part of the available energy, limiting the pressures which can be achieved as a result. Furthermore, the volume occupied by the end products at relatively low pressure become a load to the deflagration of high explosives. Therefore, the DDT process may be decelerated. In this respect laser pulse can achieve the desired heat initiation of high explosives, yet it will not interfere with the conditions for rapid pressure build-up. It is important to remember however, that achievement of the required temperature in small volume may be insufficient to initiate detonation, thus second important parameter: volumetric initiation has to be taken into consideration. This means that to realize deflagration to

detonation transition the ignition has to be created in sufficient volume. The small ignition depth in high explosives (created by EBW method, for example) cannot generate in some explosives enough gas to compensate for the volume expansion resulted from the compression of unburned high explosives under high gas pressure. The percentage heat loss rate is also larger for a smaller reaction depth. Therefore, the reaction may be rapidly quenched and terminated. Due to partial penetration of the laser beam into the explosive, laser energy can heat the explosives in depth allowing their ignition in larger volume [14]. It is expected that up to 1 mm^3 may take part in laser heating of some explosives. The thermal time constant for such volume is in range of the second, thus significantly longer than pulse duration of the free-running ruby or neodymium pulse lasers, with typical pulse duration below 1 msec. Nevertheless, reliable laser initiation of PETN and RDX explosives was achieved with this technique [14]. As it was mentioned before, free-running laser is only able to initiate burning of secondary explosive and, as it had been proved by measurement of the propagation velocity of the decomposition front, the detonation develops through DDT process in this case. Under such circumstances a significant distance in the explosive may be required for development of the transition.

The length of this distance, thus detonation development time, cannot be precisely controlled and for this reason application of this mechanism is very limited.

2.2.2 Direct initiation of insensitive explosives with Q-switched pulse laser

Shortly after laser discovery it was demonstrated that strong laser pulses can be also used for shock waves generation and various applications of this process have been proposed. One of them is application of the laser pulses for initiation of the controlled thermonuclear reaction. In this application a

high power laser pulse is used for heating, compression and confinement of deuterium plasma. This approach is under intensive research in many countries and is still considered as one of the most promising methods to achieve energy in controlled thermonuclear reaction [15].

The applicability of the laser technology for initiation of high explosives was also promptly recognized and first experiments were undertaken [16]. It was shortly discovered that laser initiation may provide higher shock wave velocities and pressures, thus can by used for initiation of the explosion in materials which could not be initiated with exploding bridgewire (EBW method). In particular, the direct detonation of tetryl, which could not be achieved by EBW method, has been achieved by laser initiation in 1967, for example [17]. This gave an impulse for further research in this field and serious effort has been undertaken in several countries (primary in former Soviet Union, USA, France and China). Presently it is widely recognized that the optical approach provides several advantages over purely electrical initiation of the explosion. These include safety increase, more precise timing, especially for multipoint initiation, better energy and power reproducibility, possible control of energy distribution across the laser beam and some other, which will be discussed latter. As a result of these recognized advantages, several programs on optical ignition of explosives were established in various countries.

Analysis of the available literature leads to conclusion that three different mechanisms can be used to create a shock wave in a target or to accelerate a thin target pellet to very high speed. The first and the least efficient mechanism is direct interaction of a high power laser pulse with an open surface of a material [18-26] (Fig. 2). In these experiments a high pressure rapidly expanding plasma is created by ablation of some amount of solid material into surrounding air or free space. The expanding plasma creates a fast moving pressure wave which can be used to accelerate a thin foil target to high velocities. The velocities exceeding 100 km/sec have been achieved

with this method. To create such high velocities, however, very powerful lasers are required because of poor energy coupling from the laser beam to solid target (laser with energy 3 kJ emitted in 3.2-nsec time pulse was applied in one experiment [26], for example). Of course, such thin foil can be used as a flyer plate for detonation of explosives. The pressure wave created by plasma can be used to generate a high velocity shock wave directly in an adjacent solid target by recoil.

In particular, such plasma can be created by rapid evaporation of some amount of the explosive, for example. The coupling efficiency of the laser energy into the plasma to some extend depends on optical absorbance of the target which varies from explosive to explosive, way how explosive was prepared and existing physical conditions. For some explosives the optical coupling efficiency can be very low and, in addition, it can be associated with low coupling efficiency of the energy from the expanding plasma into the shock wave in the explosive. All this makes the process extremely inefficient and results obtained with different explosives incomparable. To improve absorption of the laser light some strongly absorbing materials can be added to explosives (small pieces of black coal). The method can be also improved, or at least made independent of the optical properties of the explosive, by application of a very thin layer of some other light absorbing material directly on the surface of the explosive. Creation of such absorbing layer on surface of the explosive may be difficult, especially when absorbing material may chemically react with the explosive. All this causes that direct generation of shock waves in explosives by unconfined, laser generated plasma is not used in optical detonators.

Another method to create a shock wave in explosive is laser initiated breakdown inside the explosive and subsequent heating of the created plasma by remaining part of the laser energy. It was found that high explosives are partially transparent to laser radiation. This causes that radiation penetrates the explosive and laser/matter interaction involves larger

volume of the material than in the case of surface interaction with the surface of optically nontransparent materials. Necessity to heat-up of larger volume reduces achievable temperature, energy density of the created plasma and generated shock wave, thus lowering efficiency of the whole process. Analysis shows that energy density created by absorption of laser energy and associated stress is lower than chemical energy density of the explosive, thus the pressure of the plasma created due to evaporation of the explosive by laser beam should be lower than that created by explosive itself. The best-fit empirical equation of state for completely reacted secondary high explosive products foresees that pressure exceeding 100 kbars can be developed under ideal adiabatic and zero volume expansion conditions [27,28]. In reality, all explosives (especially porous) possess large compressibility under high pressure causing that maximum accessible pressure is significantly smaller, than that predicted for ideal conditions. Thus, the pressure developed inside the explosive through its direct breakdown by short focused laser pulse should be significantly lower than in the ideal case, nevertheless, it is significant for direct initiation of some secondary explosives. Observation of the detonation development speed shows, that when laser power density is higher than some threshold value characteristic for given explosive, the DDT is omitted and instantaneous detonation is observed. Efficiency comparison [11] for Q-switched lasers shows that it is lower for ruby laser with wavelength than for neodymium glass laser with longer wavelength . It can be explained as higher energy transfer rate to electrons in atoms of explosives which is proportional to the square of the wavelength in a laser-induced electron cascade breakdown. Thus threshold varies depending on applied laser and explosive. Threshold energy required to initiate detonation in both PETN (1.58 g/cm^3) and RDX (1.18 g/cm^3) explosives was over 0.65 J (above 36 J/cm^2) for 25 nsec ruby laser pulse, but there was some delay in detonation which could be interpreted as existence some transitional stage in the process. With higher energy detonation was instantaneous. Threshold for PETN for Q-switched

Nd laser depends on density of the explosive and was equal respectively 5, 7, 13 and 15 J/cm^2 for densities 1.0, 1.2, 1.4 and 1.6g/cm^3.

Similar studies [29,30] conducted with Nd:YAG its third and forth harmonics as well with XeCl excimer laser shows that detonation threshold is lower when UV radiation is applied. Probably it can be contributed to differences in interaction mechanism. It is believed that main physical mechanism responsible for initiation of explosion in this case is not thermal heating as it takes place for radiation with longer wavelength, bur structural breakdown and ionization of the explosives with UV radiation. The studies have also demonstrated that there is significant threshold decrease when surface of the explosive is covered with transparent quartz plate. This caused that the plasma created at the surface of the explosive has limited expansion capabilities resulting in higher pressure development, thus reducing threshold laser power density of explosion.

The above mentioned experiments have also demonstrated that the pressure achieved with unconfined method applying a simple single stage laser is insufficient for initiation of detonation in more resistant explosives. Furthermore, because of volume interaction of the laser radiation with explosives, the process strongly depends upon various factors including chemical structure of the explosive crystal, defects of its structure and impurities such as small foreign particles. All this together leads to poor reproducibility of this technique causing that it is practically not used for detonation of the high explosives and presently two other methods are under intensive research.

2.2.3 Thin film shock wave generation in insensitive explosives with Q-switched pulse laser

Detailed study [31] of Q-switched laser pulse interaction with metals has demonstrated that when power density of incident beam is strong enough, the front part of the laser pulse is used to evaporate and ionize of some (relative small) amount of metal creating plasma which strongly absorbs incident radiation. As a result, majority of laser energy is not used for evaporation of material, as it takes place for low-energy laser interaction, but to increase the temperature of the created plasma. Because of that, the general effect is practically independent on optical and thermal properties of the initial material and mainly depends on optical and thermodynamic properties of the high-temperature plasma, which are practically independent of the material applied. Thus, covering of the explosive with a thin metallic layer makes the system independent of the reflexivity of the applied metal, its specific heat and specific heat of evaporation. As it was explained before, such high temperature plasma tends to expand rapidly exerting pressure on surrounding media, including non-evaporated part of the metallic layer, which may transfer the pressure to the explosive [32,33]. Unfortunately, in the case of the unconfined plasma, efficiency of the energy transfer from the plasma to explosive is low and to achieve significant pressure very powerful lasers have to be applied. This approach is often used for laser controlled thermonuclear experiments and pressure in TerraPascal range has been achieved [23,26]. For example, by focusing on the surface of the aluminum target laser pulses of 300 psec in duration with energy 66 J or 100 J into a spot of 0.6 mm in diameter, the power densities $8x10^{13}$ W/cm^2 and $3x10^{14}$W/cm^2 were created which produced pressure 0.6 TPa and 1.8 TPa respectively in the target. The pressure achieved in such experiment is more than sufficient for initiation of majority explosives, but required energy and power can be achieved with very large laser systems only. This makes the above approach infeasible for initiation of explosion and more efficient solution had been sought.

The main reason of low efficiency of the process is poor acoustical impedance match [23] between the expanding plasma and the target and resulting from this poor power coupling from plasma to explosive. This effect can be significantly enhanced, however, using so-called spatially confined plasma [11,16,17,21-23] and all further experiments with laser initiation of high explosives were performed under confined conditions. Technically it is realized by using a transparent glass or fused silica plate coated with a metallic layer being in a direct contact with the explosive (Fig. 3). The laser beam has the access to the metallic layer through the substrate and when the layer is exposed to a high power laser pulse the plasma is created between the substrate and the layer. The high pressure wave created by the expanding plasma generates a shock wave in surrounding media, which is transferred to the explosive directly (if all absorbing material has been evaporated) or through the unevaporated part of the layer. Using this method the various densities PETN and RDX were initiated with initiation strength below 100 kbars using relatively low power laser [13,32,33]. Other materials requiring of higher initiation strength were not tested initially.

The detailed study of the process [18,19,31] using nanosecond range laser lead to following conclusions:

1. At least for 25 nsec laser pulse the generated stress increases during whole peak duration time and reaches maximum at the end of the pulse. Fall time of the stress is also of the same order of magnitude.

2. The peak stress is proportional to the total energy of the pulse and for 25 nsec pulse reaches 22 kbars at 14 J/cm^2. The linear dependence is probably valid up to about 80 kbars which was achieved at 56 J/cm^2 energy density. Beyond that limit, the stress probably will be an increasing function of the total energy.

3. The peak stress does not depend on applied material.

4. The peak stress does not depend on thickness of the absorbing film except for high thermally conductive metals and low total energy.

5. Layer of thickness of several hundred Angstroms is sufficient for generation of shock wave through evaporation of the metallic layer.

6. For pulse energy up to 5 J majority of laser energy is lost or used for ionization and ablation and only about 10% of energy is converted to stress energy.

As it follows from the above description, generation of the shock wave in explosives by laser evaporation of the metallic foil being in direct contact with the explosive has several advantages. The direct contact of the metallic foil with explosive has also some important disadvantages which include possible chemical interaction of the metallic foil with explosive and technical difficulties in creation of the detonator in which very thin foil (several to a few tenths of microns), has to be brought in a close contact with the explosive. Technically it is much easier to create a detonator with these two elements separated. The above conclusion leads to development of the concept similar to electrically driven flyer plate.

2.2.4 Laser driven flyer plate

Similarly to electrically driven detonator [9], laser beam can be used to launch a small flyer plate with high velocity, impact of which on the explosives creates a shock wave required for initiation of the explosion. Initially [34,35], applicability of the laser beam for acceleration of a thin metallic foil was tested under unconfined conditions, by direction of relatively low power density laser beam into stretched in space foil. Behavior of the foil was observed with **O**ptically **R**ecording **V**elocity

Interferometer System (ORVIS). The aluminum foil of 2-200 was irradiated with 10 nsec light pulses generated by Nd:YAG laser. 0.7 J energy generated by laser was focused into spots about 1.5 mm in diameter. This generated power density up to 3-4 GW/cm^2. As can be expected, velocity strongly depends on initial thickness of the foil and decreases with foil thickness increase. Velocities up to 1.5 km/sec have been achieved with this method for foil of 2 thick. The acceleration time was approximately equal to pulse duration, independently on thickness of the foil. It was found that efficiency of the energy transfer in this process was very low, in a range of a single percent, and with the above mentioned laser was insufficient to initiate explosion neither in PETN (density 1.4 g/cm^3) nor in HNS-FP (density 1.6 g/cm^3), thus experiments with confined plasma were undertaken.

Experiments conducted with confined plasma [36] applying similar to the above but slightly more powerful Nd:YAG laser (3.5 J pulse in 16 nsec time) have demonstrated that the flyer, generated by the laser beam focused through the fused silica substrate (Fig. 4) into spot of 1.5 mm in diameter (power density over 10 GW/cm^2) on the surface of the aluminum foil, may attain significantly higher velocity than in the case of free standing foil. Estimated energy transfer from the laser pulse to the flyer was about 25 times higher (up to 25%) resulting in almost 5 times higher velocity for the flyer of the identical thickness. About 0.8 J of energy delivered by flyer was sufficient to initiate the explosion in the above mentioned explosives.

Significant increase of the efficiency of energy transfer from the laser pulse to the flyer can be achieved by using multiple layer flyer plate for production of detonator [38,39]. The proposed multilayer flyer plate is made on a UV-grade quartz substrate and consists of three layers (Fig. 5). The thickness of the first metallic layer which is deposited directly on the quartz substrate is selected in such a way that it absorbs practically all incident light but is thin enough to be fully converted to a rapidly expanding high pressure plasma. The second, dialectical layer less than 0.25 usually made of material

(aluminum oxide) which has a higher shear strength than aluminum and relatively low thermal conductivity, preventing the rapid conductive cooling of the plasma, thus helps to increase its pressure before the layer breakdown. The third layer made of aluminum or copper 2-10 thick, plays the role of an actual slapper material and small piece of it is launched as a flyer plate. This configuration increases efficiency of the energy transfer from the laser pulse to the slapper to over 50%. If illumination area is sufficiently large (a few hundreds micrometers) flyer plate preserves planarity at the impact at least at short distance. With this technology flyer plate 2-10 thick, 0.4-1.0 mm in diameter was accelerated up to velocities over 5 km/sec with 10 nsec long, 30-300 mJ light pulse generated by Nd:YAG laser. The slapper generated in such a way was sufficient to initiate a prompt explosion in various explosives. This successful illustration of applicability of laser radiation for initiation of high explosives risen a significant interest to this technology and further research have been undertaken.

2.2.5 Slapper detonator system with fiber-optic delivery system

It was shortly realized that initially applied approach with laser beam directly delivered to the flyer creates significant technical difficulties which are unacceptable for some applications and need arisen to separate the laser as a source of light pulse from the detonator itself. This can be done using optical fibers for light transmission between the laser and detonator [40-42]. In this case the laser energy is coupled into optical fiber at the end of which an optically initiated slapper detonator is placed (Fig. 6) [43]. There are several advantages of such solution. The first one is complete separation of the control electronics, vulnerable to electromagnetic interference, from the explosive which eliminates possibility of their direct interaction. In particular, if electronic part is blown-out by strong blast of the electromagnetic radiation (nuclear explosion, for example) it will not initiate detonation as long as laser pulse is not delivered to the detonator. It is highly improbable that precise timing needed for generation of the Q-switched laser

pulse will be achieved unintentionally in a laser system strongly disturbed by electromagnetic interference. Certainly, this will significantly increase the safety of the weapon equipped with such kind of the detonator. Another advantage of laser initiated detonator with fiber-optic light delivery system is possibility of the precise synchronization of the explosion simultaneously in many points using a laser pulse generated by a single laser, devided into a required number of the beams and delivered to particular optically triggered detonators by means of optical fibers of carefully selected lengths. This approach provides significantly better synchronization control than it is possible with electronic circuits and at the same time, as it was mentioned before, such system is resistant to electromagnetic interference. It seems that for all these reasons laser initiation of explosives, especially with fiber-optic light delivery system is considered as extremely important and it provides justification for this project.

2.3 Parameters influencing performance of the optical detonator

As it was mentioned before, the purpose of the optical detonator is to provide a safe, resistant to electromagnetic interference, reliable and securing the high timing precision for initiation of the secondary explosives. Precision of such detonator depends on many factors including precision of the electronic control system and reproducibility of the detonation development process. Duration of this process for given explosive depends on applied method of initiation and it is hardly controllable if initiation is realized through DDT process. In this respect every detonator can be characterized by two parameters the excess time t_{ex} required for full development of explosion from the moment of ignition and probability p of the detonation as a function of time [44]. The shorter this time and smaller standard deviation of probability function are the better detonator is.

The parameters that can affect t_{ex} and p are listed below The parameters are separated into three different groups:

1) parameters related to the shock wave inside the explosive material,
2) these related to the laser-material interaction,
3) and parameters related to the flyer plate. For flyer-type detonator the initiation depends on the parameters listed in all three groups while for shock-wave detonation only the parameters of first two groups are involved.

1) Detonation in the explosive material:

- explosive itself
- powder particle size
- density
- shock wave peak pressure
- shock wave duration
- its area

2) Laser-material interaction:

- power of laser pulse
- pulse duration
- spot size
- wavelength of light
- type of absorbing material
- its reflexivity
- thermal conductivity
- confinement (window material)

3) Flyer plate:

- velocity
- density
- surface of the flyer
- thickness
- planarity

Analysis of available literature leads to conclusion that there does not exist sufficient experimental data allowing selection the best combination of all these parameters. In addition, various experimental data were obtained under different, often incomparable conditions. In this situations to produce high quality final laser driven detonator further extensive, targeted studies are necessary.

3. STUDY OF THE PHYSICAL PROCESSES ASSOCIATED WITH DETONATION

3.1 Initiation of the detonation

The physical processes involved in development of the detonation in the explosive are well understood and have been described in numerous publications. Good overview of these publications can be found in references [1-8] (some additional information can be found in references [45-51]). The short summary of present knowledge in this field is given in previous chapter which in relation to secondary explosives may be summarized in the following way.

There exists agreement that to initiate the secondary explosive by means of the slapper, a shock wave of sufficient strength (wave speed 1-5 km/sec and pressure in GPa range) has to be generated in sufficiently large volume of the explosive. In case of the slapper it is reasonable to assume that the volume of the excited explosive is related to the area of the slapper and its speed. When the area is too small (diameter smaller than 0.1 mm), created shock wave can be considered as a spherical even at short distance, which results in strong divergence of the shock wave and fast energy dissipation in

the explosive. This causes increase of the required energy with decrease of the diameter of the slapper. For larger slapper, at short distance from the slapper entry into explosive, initial wavefront shape can be considered as plane with smaller dissipation of the energy. Thus, such slapper provides better ability to compress explosive in sufficiently large volume and create pressure build up required for initiation of the detonation. In this situation it has to be expected that required slapper diameter and its speed should depend on compressibility of the explosive and for more porous materials probably larger slapper will be required for reliable initiation. For slapper with diameter larger than 0.1 mm, the energy required for initiation of explosion does not change so dramatically with diameter and remains almost constant, which means that initiation speed is smaller for larger diameter but it has to be still higher than some threshold value. It is evident that to achieve this threshold speed value, the required energy will rise with diameter of the slapper. Taking into account all these constrains, it was found that the slapper with diameter not smaller than 0.25 mm, accelerated to the speed higher than threshold required for given explosive, provides reliable initiation. It seems, that optimal slapper diameter may depend on applied explosive, its granularity in particular. Experiments [30,44] show that required shock wave pressure is smaller for smaller grain size. At the same time more energetic excitation is required to initiate denser explosives i.e. these being under higher pressure. In this respect pulse initiation differs from DDT transition when faster transition is observed in explosives being under higher pressure. In general, it was observed that the reproducibility of the detonation increases when the applied pressure, thus applied laser power and energy densities are significantly higher then the threshold values.

There exist significant difference in development of the detonation mechanism with application of the laser beam directly and through slapper production process. When the shock wave is generated by the impact of a flyer, the threshold value of the product of the squared required pressure and

duration of the pressure pulse remains constant for given explosive, i.e. for lower shock wave pressure longer interaction is required [44,49]. At the same time, when the shock is directly generated by a short laser pulse (no longer than 25 ns) no significant difference is observed [30,49]. It can be explained by the presence of the hot plasma which may accelerate DDT process through the strong influence of hot spots [49].

3.2 Laser generation of the slapper

The physical mechanism involved in laser production of the slapper applicable for initiation of the secondary explosives were extensively studied by many authors [36-42] and general picture is quite clear, however, it seems that many details are still missing. There exist general agreement that the most efficient way to generate flyer plate using optical method is confined plasma mechanism when laser beam is used to evaporate a small part of an absorbing material confined between some transparent substrate and a layer of the material used to generate a flyer plate. To generate flyer efficiently, optical energy has to be delivered in a sufficiently short pulse, i.e. the pulse laser of sufficient peak power is required. Literature reveals that to launch a flyer with energy sufficient for initiation of the secondary explosive optical power density of several GW/cm^2 is required. This means that required power of laser beam should be in range of 10 MW for slapper 0.25 mm in diameter, which is equivalent to about 100 mJ of energy for laser pulse duration of 10 nsec.

The optical generation of slapper process consists in transfer of energy from laser beam into kinetic energy of flying slapper. The process develops differently depending on duration time of the incident laser pulse providing required energy. For pulses with the duration time in range of nanoseconds the whole process can be divided into several steps. In the first step, a part

of laser pulse is absorbed by a thin layer of light absorbing, usually metallic material. In this stage absorbed light energy is used to heat absorbing layer, which rapidly reaches evaporation temperature and evaporates. Due to further absorption of light vapors are transformed into plasma, efficiently absorbing remaining part of laser light. Absorption of this part leads to rapid heat-up of the plasma resulting in the impetuous pressure build-up which is transferred to the surrounding media in a form of the pressure or shock wave. The shock wave can be directly coupled to the explosive [20] or associated pressure wave can be used to eject a small piece of solid material which may act as a slapper [36].

It seems justified to suppose that in this process thermal conductivity of the absorbing material may play an important role. It may influence speed and quantity of the evaporated material, thus the thickness of ablated layer and explains observed dependence of the process on pulse duration. When laser energy is delivered in shorter pulse, all thermal processes are omitted and plasma is created immediately as a result of destruction of the molecular and chemical bonds by electromagnetic field. In this situation the thickness of the ablated layer is defined by penetration depth of the optical radiation into the absorbing metallic layer. Transition from one kind of the mechanism to another probably depends on various factors and presently it is not clear at what duration time of the laser pulse it occurs. It seems that transition between these two behaviors lays somewhere in nanosecond or subnanosecond time range and may depend on applied material and achieved power density.

These changes in physical mechanisms leading to creation of the plasma are probably responsible for a certain confusion in the estimated thickness of ablated material. Some authors [20, 38, 41] consider the thickness of the ablated material as the skin depth calculated at the laser wavelength (for Al and laser wavelength of 1.06 , = 6 nm), and close to this values is provided by many authors. If thermal effects are taken into account, the estimated

ablation depth is related to thermal conductivity and pulse duration in the following way [31,52]:

The thickness of ablated layer calculated from this formula varies in wide range from tenths of nanometers up to ten micrometers. The last value is close to obtained experimentally (13) by measurement of the difference in the thickness of the light absorbing layer and generated slapper [36]. Experiments conducted at NOI also suggest that thickness of the ablated layer is in a few microns range.

While radiation of different wavelength was used in study of laser shock wave generation process and for slapper generation, the number of practically acceptable lasers which can efficiently deliver required energy in acceptable time is very limited and practically only Nd lasers can be seriously considered as energy sources for slapper detonator. Standard pulse duration of these lasers is in range of several nanoseconds and pulses with of this duration were used in research on the laser generated slapper. Advantages of these lasers include their high energetic efficiency and compactness of the systems. Unfortunately these systems are not able to provide significantly shorter pulses and it is not clear if application of lasers with shorter pulses may have significant advantages. We belive that this is an important issue and more detailed research on applicability of significantly shorter pulses for flyer launch should be undertaken. Such kind of research in application to laser-matter interaction is already conducted in Canada at INRS in Varenne. The INRS has very powerful laser system able to provide pulses whose width may vary from femtosecond to nanosecond range with energy sufficient for slapper launch. This facility is available for research covered by the present program and a preliminary agreement has already been arranged with Prof. J.-C. Kieffer.

Diameter of laser spot used in these research varies in a wide range from part of the millimeter to about two millimeters. Distribution of light across the

spot may vary in wide range. Multimode lasers were used in first experiments which did not provide controlled intensity distribution across the spot. Presently beams with Gaussian profile are mainly used. Beams with such profile deliver nonuniform intensity distribution, which interact with absorbing layer in nonuniform way and, as a result, create strongly deformed flyer plate. Our tests have demonstrated that shape and size of slappers produced with such beam vary in wide range. It seems that quality of the slapper is significantly improved when multimode fiber-optics delivery system. In this case diameter of the beam is defined by core diameter of the fiber. Typical core diameter of fibers applied in such system is about 0.2 mm. This means that delivered light has multimode structure i.e. beam consists of many spots a few micrometers in diameter. Because of small diameter of the spots, they are not recognized by absorbing layer and light beam is perceived as uniform with diameter equal to that of fiber core. Bringing all arguments together, it seems, that slapper of 0.2 mm in diameter are optimal for majority applications and spot size of laser beam have to be adopted to create such slapper.

Various research lead to conclusion that the flyer speed is crucial for prompt initiation of the detonation, thus size, thickness and material of the flyer should be properly selected. It is evident that with given energy the largest speed can be achieved with for the flyer with the smallest mass, thus density and size of the flyer have to be minimized. At the same time, however, area of the flyer is crucial for efficient initiation of the explosive and practically it cannot be reduced below some critical value and as it has been explained above flyers of 0.2 mm in diameter should be considered as optimal. This means that only parameters available for optimizing are thickness of the flyer and density of the applied material. In this respect it becomes evident why best results have been achieved with aluminum, which has one of the lowest densities. Thickness of the flyer cannot be reduced infinitely because it mechanical strength is directly related to the thickness. In this situation some compromise is necessary and usually flyers a few micrometers thick

are used. Because of partial evaporation of the flyer by laser pulse, the initial thickness of the material used for its production has to be larger and difference between initial and final thickness of the flyer increases with pulse duration and thermal conductivity of the applied material. To satisfy all these requirements initially the flyer material should be at least several micrometers thick (in some experiments over 20 thick layer was applied). Production of such thick layer well adhered to the substrate is not easy task and special deposition methods have to be applied. The most often electrochemical deposition is applied.

The final and very important parameter is planarity of the produced flyer. As it was mentioned before, dissipation of the shock wave energy plays an important role in initiation of the secondary explosives, and flyers with good planarity are required. It is obvious that to obtain good planarity the pressure of the created plasma should act uniformly on whole surface of the flyer. This means that plasma should also be generated in uniform manner, which probably can be achieved with light beam which provides uniform power density distribution. The influence of the spatial light distribution across the absorbing layer on planarity of the flyer has not be studied in details and this may be a field for further improvement of performance of the slapper detonator. In particular, laser beams with non-Gaussian intensity distribution may give some advantages. Such beams can be created by transformation of the Gaussian beam by means of suitable diffractive element. The National Optics Institute possesses all required expertise and technical capabilities to create such elements.

It become evident in this context that to reduce energy and power requirements and to optimize all design parameters of the slapper detonator more detailed research of these problems is required.

4. PRELIMINARY TECHNICAL EXPERIMENTS

To gain better recognition of technical problems associated with laser generation of flyer plate, some preliminary experiments have been undertaken. The experiments included production of thick metallic layer on glass substrate and generation of the flyer itself with pulse laser.

4.1 Preparation of the metallic layer.

As it was mentioned before, layer of at least several micrometers in thickness is required for laser flyer generation. Creation of the layer of such thickness by evaporation is extremely time consuming and we decided to use electroplating method. Because of electroplating can be applied to electroconducting materials only it was necessary to create some conducting layer on the surface of the glass or silica substrate. Several materials were applied but shortly it was found that majority of them were dissolved in electroplating bath before required layer was created. After several tries we found that chromium layer had sufficient resistance. At NOI we did not have a big choice of the materials for electroplating process and we were forced to use copper as a material for the flyer. The first experiments demonstrated that adhesion of the copper to chromium was bad. To improve adhesion an additional cooper layer was evaporated over chromium layer. This slightly improved adhesion and several samples were produced in such a way, which were used in further experiments. The best results were obtained with copper layer 20 thick.

4.2 Experimental research.

Experiments were conducted applying Nd:YAG laser with wavelength about 1.06 in the system shown in Fig. 7. The Q-switched Nd:YAG laser provided reliable laser pulses with time duration about 10 nsec when voltage on the capacitor battery was significantly higher than threshold value. Under this condition delivered energy was too high and it had to be limited. A half wave plate and thin film polarizer were used for controllable attenuation of the laser energy. The beam was focused on the target with a long focal length lens. The central part of the beam was selected by means of diaphragm to secure uniform intensity distribution across the beam. Small parts of the laser energy were taken by means of the diffractive sampler for energy and beam quality monitoring systems. The part transmitted through the Holographic Beam Sampler (HBS) was used to create the flyer. A glass plate placed very close to slapper was used to recover the flyer. It was found that diameter of the laser spot in the focus was about 0.32 mm. Observations had demonstrated strong dependence of the flyer quality on applied energy, and the flyers of the acceptable quality were generated only when incident energy density was very close to the optimal value. If energy density was too small it was insufficient to launch the flyer. For too high energy the multifragmented flyer usually was produced. Thus, the acceptable quality flyers were observed when for power densities around 1.75 GW/cm^2, which corresponds to total energy of the pulse a little above 14 mJ. These values are close to those published in literature. It was also observed that travelling distance of the flyer in space is very short and it was impossible to recover flyer at larger distances. There is no final prove, but it seems that travelling of the flyer in air leads to its destruction. The reason of destruction is not clear but it may happen that friction of the flyer with atmosphere increases its temperature and leads to consecutive rapid oxidation which ends with its total destruction. Several pictures of the remnants of the slapper on recovering glass are shown in Fig. 7.

The experiments confirmed that it is possible to create flyer plate using laser pulse of the sufficient strength. It has also demonstrated that production of the flyer plate material is not easy and further research is necessary to find the best design of the detonator, its production technology, proper material and thickness.

5. DIAGNOSTIC METHODS OF LASER LAUNCHED FLYER PLATE

Analysis of available literature, the above conducted experiments and research conducted in this field at NOI (together with DREV) on diagnostic technology of the slapper detonator partially presented in reports [53,54], lead to conclusion that development of slapper detonator without proper diagnostic instrumentation is impossible and quite extensive diagnostic systems are required. It seems, that to cover the most important aspects of development program related to laser driven slapper detonator three major systems are necessary:

- streak camera for registration of the detonation development process in explosives to discover at what parameters instantaneous detonation is achieved (streak camera suitable for the task is available at INRS);

- flyer speed measurement system has to be specially developed (several possible systems are described below);

- flyer shape measuring system (system earlier developed at NOI can be used to serve this task).

5.1 Diagnostic of explosion development process

Number of measuring techniques applied for research of various aspects of detonation process is very large. Many of these techniques are described in books related to this topic ([1-3], for example) and will not be discussed here. The most important among them for development of fiber optic slapper detonator is technique allowing measurement of propagation speed of reaction front, since this speed allows to distinguish different stages of the detonation development process.

Measurement of the speed of the detonation development process is straightforward and consists in registration of the propagation of the reaction front in a column of the explosive encapsulated inside of the high pressure cylinder, by means of a streak camera through the transparent window made in the side wall of the cylinder. The image of the explosive is projected on the slit of the camera which is oriented along the axis of the cylinder. Appearance of light in the slit of the streak camera provides information on development of detonation process. This is a standard technique described by many authors [1-3] and will not be discussed here.

5.2 Flyer speed measurement

Essentially three techniques are used for speed monitoring of a flyer plate during flight:

- Michelson interferometer with a flyer plate used as one mirror of the interferometer,
- Fabry-Perot interferometer used as a spectrum analyzer for light reflected and scattered by a flyer plate,

- VISAR Velocity Interferometer System for Any Reflector in which light reflected by flyer plate is directed to unequal path interferometer with electronic registration of the interference pattern,
- ORVIS is equivalent to VISAR but interference pattern is recorded optically with fast streak camera.

Michelson interferometer generates fringes with frequency proportional to the object speed. The fringe is generated each time when target translates by a half wavelength of applied light i.e. approximately every quarter of micrometer when argon laser is used as a source of light. For speed 5 km/sec this corresponds to frequency 20 GHz. Registration of such high frequency process is extremely difficult and for this reason Michelson interferometer is not used for diagnostic of such high speed processes.

It is well known from basic courses of physics that wavelength of light reflected or scattered by moving object is different from that of the incident beam. This is known in physics as the Doppler effect. The wavelength of scattered light depends on initial wavelength of light and speed of the object in following way:

$$\lambda_D = \lambda \left(1 \pm \frac{v}{c} \right)$$

where c is the light speed; the sign inside of parentheses is negative when the target moves toward the optical measuring system and positive for movement in the opposite direction.

The changes of the wavelength is measured with high resolution Fabry-Perot interferometer. Because of high velocity of these changes this is usually registered by means of a streak camera. Sensitivity of the system and its reaction to the speed changes are relatively slow and for this reason this approach is seldom presently used. Advantage of this solution consist in that

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streak camera used for observation of detonation can be also used for speed registration.

VISAR is another interferometric system applied for speed measurement. It usually consists of modified unequal path Michelson interferometer. The main difference is that light reflected from moving target is directed to interferometer where it is divided into two parts travelling separate legs of the interferometer. Optical path difference causes that interfering light comes from the same flyer but with time delay defined by optical path difference of the legs of the interferometer. If speed of the flyer remains constant, interference fringes remain unchanged as for stable object. If, however, object is rapidly accelerating, light arriving at different time is Doppler shifted by different amount. This is perceived by interferometer as a shift in position of the interference fringes and can be detected by suitable electronic system. The number of fringes $N(t)$ detected by the interferometer is a function of time and depends on optical path difference δ of interferometer legs, wavelength of applied light λ and temporary object speed $v(t)$, in the following way:

$$\frac{dN(t)}{dt} = \frac{2\delta}{c\lambda}\frac{dv(t)}{dt}$$

The integration of this formula leads to the dependence:

$$v(t) = v_s N(t)$$

where v_s is so-called characteristic speed of the system and is equal to:

$$v_s = \frac{c\lambda}{2\delta}$$

As it follows from the above, the number of registered fringes can be regulated by proper selection of the characteristic speed of the system, which is simply related to the optical path difference. Direction of the fringes

movement is related to sign of acceleration and simple detection of fringes translation is not sufficient to recognize the actual speed. To remove this ambiguity, additional information on fringes translation direction is necessary. This can be resolved with second detector of fringes shifted in phase by about . This usually is produced by proper shift of spatial position of the second detector in field of view. The system has an important advantage consisting in that its sensitivity can be adjusted depending on speed of the object, to create number of fringes easily registered by an electronic system.

The ORVIS system is nothing else like VISAR with optical recording of the interference fringes by means of streak camera. Probably precision of such system is lower than sensitivity of that with electronic registration, but if such camera is available it may significantly reduce price of the whole diagnostic system.

5.3 Planarity measurement

Instruments applied for planarity measurements were discussed in details in two reports [53,54], already available at NOI and DREV, thus they will not be discussed here, nevertheless some valuable data on various aspects of detonation process and related diagnostic methodology can be found in additional references [55-68]. It is important to mention here, however, that under contract from DREV the National Optics Institute has developed an unique holographic microscopic system for 3D registration of flyer plate in flight [54]. This system can be used as valuable tool for shape diagnostic of flyer in flight.

6. CONCLUSIONS

The analysis of the needs and the above presented state of research in field of laser initiated slapper detonator leads to following conclusions.

1. Due joint thermal and shock effect lasers may be used for reliable initiation of the explosives resistant to initiation with other available methods.

2. Laser as additional step in power conversion and control system of detonator increases handling safety of warheads containing high explosives.

3. For the same reason laser based detonators are more resistant to electromagnetic interference and electromagnetic shock associated with nuclear blast.

4. The light controlled detonators allow better synchronization of the detonation in warheads with multiple points initiation.

5. There exist two technically feasible methods applied for laser initiation of high explosives:
   - through direct initiation of shock wave in explosive;
   - through generation of high speed flyer plate.

6. In both cases spatially confined plasma only secures sufficient efficiency of the process.

7. The first technique can be used for initiation of the pressure pre-loaded explosives, since substrate for light absorbing material can be also used as a pressure sustaining window. Disadvantage of

the method is direct contact between detonator and explosive and uncontrolled development of the shock wave.

8. By careful control of the flyer shape it is easier to control development of the shock wave in the explosive. Another important advantage of the slapper detonator is its separation from the explosive. The main disadvantage is free space between detonator and explosive which causes that it cannot be used for initiation of pressure pre-loaded explosives.

9. In both cases the fiber optic energy distribution system can be used for multiple point initiation of the detonation.

10. All these advantages justify development of the laser controlled detonator.

7. IDENTIFICATION OF THE MOST PROMISING DESIGNS OF SLAPPER DETONATOR.

The analysis of the available literature leads to conclusion that data presented in literature is not sufficient to make final selection of the best design laser controlled slapper detonator. Each of two methods: direct generation of shock wave and generation of the wave by mean of flyer plate have some advantages and disadvantages and presently is impossible to judge which is the best. In this situation further research on both method have to be conducted. It seems, however, that application of optical fibers for energy delivery from laser to the detonator has definite advantages over free space delivery system. These include separation of the laser and detonator and easy synchronization of the detonation for multiple point initiation. For this reason fiber optic approach seems to be the best choice. The main disadvantage of the fiber optic system consists in that power

density which has to be transferred through the fiber (several GW per cm^2) is close to surface damage threshold of the majority optical materials and is extremely sensitive to surface imperfections of these materials. These imperfections include dust, scratches and all kind of dirt on the surface. Thus, the surface quality of the fiber ends is crucial factor which is extremely hard to control over long time period. The only logical solution in this situation is generation of the relatively low power laser pulse using special seed laser, coupling of the laser beam into the fiber and amplification of the laser pulse inside the fiber. Power of the laser pulse has to be settled on such level that probability of the damage of the fiber end is acceptably low. To achieve required power laser pulse should be amplified to suitable level inside the fiber. This means that operational wavelengths of seed laser amplifying fiber should be identical. It seems that because of high energetic efficiency the neodymium doped YAG crystal or glass lasers are the best choices for such application. For technical reasons it is difficult, however, to produce optical fibers made of YAG crystal and in this context Nd doped glass fiber has to be considered as the only candidate. It is important to point out at this moment that the idea of the fiber optic detonator with amplifying fibers used for energy delivery was not presented in literature before and has been developed at NOI. It may happen that this concept is an original contribution of developing team and should be protected by suitable patent application.

8. IDENTIFICATION OF INITIAL LASER AND MATERIAL PARAMETERS

As it follows from the available literature the role of the flyer in a slapper detonator is to create in some area of the explosive a shock pressure wave sufficient for development of the self-propelling detonation wave in the explosive. It is extremely important at this stage to secure such propagation conditions for shock wave that it propagates without significant attenuation through a suitable large volume of the explosive. Even if the shock wave is not absorbed, the power density decreases as a square of the distance for the spherical wave, while it remains unchanged for the plane one. For real, absorbing materials the volume within which the energy is dissipated also increases faster for divergent than for plane wave. It necessitates creation of the plane pressure wave. The characteristic property of such wave is plane phase front and uniform power density across the wavefront. It is obvious that such wave can be generated by a flat flyer only with uniform distribution of the kinetic energy across the surface of the flyer. Since kinetic energy is given by the half product of the mass multiplied by squared velocity, it is clear that these conditions can be secured by the flat flyer with constant surface mass density whose all parts progress with the same velocity. To initiate detonation, however, it is necessary to secure sufficient compression of the explosive in a suitable short time. It can be achieved if velocity of the flyer and delivered energy density are higher than some threshold values for the given explosive. This automatically means that energy of the flyer has to rise with its cross section. In this respect it is extremely important to find optimal size of the flyer and to secure its planarity.

Experiments conducted with electrical driven flyers as well as earlier described experiments with optically driven flyers lead to conclusion that for sufficiently fast flyers (velocity in range of 3 km/sec) detonation development distance is so short that pressure waves generated by flyers around 0.2 mm in diameter behave as plane ones on the above mentioned distance. This gives a clue regarding size of the flyer of future slapper detonator. The exact size has, however, to be found through the more detailed theoretical and experimental study of the problem. Nevertheless, the flyer 0.2 mm in diameter will be considered as a fair reference for all future estimations.

To secure high efficiency of the process, the energy has to be delivered to the slapper in time short enough to prevent conductive heating of the larger volume of the material used for production of the slapper detonator. It is known that the heat in solids is transferred through collision effect, thus this is determined by speed of molecules which is comparable to the sound speed in the material under consideration. In solids this speed is in the range of a few km/s which corresponds to a few μ/ns, thus, to prevent significant dissipation of the energy in a form of the heat, the energy has to be delivered in time not longer than a few nanoseconds. This means that Q-switched laser able to generate laser pulses not longer than several nanosecond is required. It is obvious that energetic efficiency of the laser is also important. Presently Nd:YAG and Nd:glass lasers provide the highest overall efficiency in Q-switch mode, which can reach up to several percents. For all these reasons they seems to be ideal candidates form these applications and because of difficulties with creation of YAG fibers, the Nd:glass laser remains the only candidate.

As it follows from the above considerations, there exist several important parameters determining quality of slapper detonator: total kinetic energy delivered to the flyer by detonator, speed of the flyer, its size, planarity, energy and power densities delivered to explosive, and so on. If velocity of

the flyer is not high enough, it would not initiate detonation in the explosive, even if otherwise delivered kinetic energy could be sufficient. Thus, the flyer with suitable speed and energy is necessary to initiate explosion.

As it has been explained above, the kinetic energy E_k of an object is equal to the half of the product of its mass m by its squared velocity v, thus, if the kinetic energy remains unchanged the increase of the speed will be possible by reduction of the object mass only. Having the required kinetic energy E_{kr} and the speed v_r, the mass can be found from the formula:

$$m_r = \frac{2 E_{kr}}{v_r^2}$$

For a material with a given specific density ρ and flyer radius r_r the thickness h of the flyer can be found from the dependence:

$$h = \frac{m}{\pi \rho r_r^2} = \frac{2 E_{kr}}{\pi \rho r_r^2 v_r^2}$$

Simple calculations show that for typical total energy of the flyer in the range of 10 mJ and required speed not smaller than 3 km/sec, mass of the flyer should not be greater than 2 *mg*. The above means, that for a flyer 0.2 mm in diameter, made of material with specific density about 3 g/cm^3, the thickness of the flyer should be in range of 20 μm and proportionally smaller if the flyer is made of denser material. This gives idea of approximate size and mass of the flyer. Energy necessary to launch such a slapper depends on conversion efficiency of the light energy into kinetic energy of the flyer. Described in the literature systems typically secure 25% efficiency, which means that light energy delivered to the detonator has to be at least four times higher than kinetic energy of the flyer. Thus, to launch such slapper about 40 mJ of energy is required. The energy has to be delivered in time of several nanosecond to the surface about 0.03 mm^2 large. This gives energy

density about 130 J/cm^2 and power density in range of 40 GW/cm^2. This is far above the surface damage threshold for all optical materials and if this power density has to be delivered through the optical elements its reduction is necessary.

There are several ways to reduce this power density. One of them is to increase duration of the laser pulse. Problem is that increasing the pulse duration may reduce efficiency of whole process and very careful optimization of this time is required. It is clear, however, that it will be impossible to reduce power density to acceptable level on this way only and it is unlikely that pulses significantly longer than 15 nsec, which could result in 5 times reduction of power density, will be acceptable for this application. The second approach is increasing of the energy transfer efficiency from the laser pulse to the flyer. The transformation efficiency of the optical power into the kinetic energy of the flyer can be improved up to 50% using specially designed multilayer flyer element. This will additionally reduce required power density by factor of two. Nevertheless, taking into account possible losses in the delivery system used for transportation of the optical energy from the laser to the detonator (optical fiber, for example), energy of the laser beam has to remain sufficiently high, which leads to conclusion that minimal required laser energy should be several times higher than required kinetic energy of the flyer, probably in range of 0.1 J for a single point detonator. It is understandable that total required energy has to be multiplyed by number of detonation points for multiple point detonator. Furthermore, the energy has to be additionally increased for detonators with larger flyer.In principle, this energy can be directly delivered to the detonator by standard optical means: mirrors, prisms and lenses and it should not create any significant troubles. This approach, however, has many disadvantages, which were discussed before, and in this situation the fiber optic delivery system is preferred, especially for multiple point detonation systems. This is a reason why we propose development of the detonator based on the fiber optic solution. This solution means that the laser pulse has to be coupled into optical fiber, which will carry it to the detonator.

If optical fiber is used for light delivery, all required energy has to be concentrated on the entry end of the fiber. If fiber core diameter is equal to the desired diameter of the flyer (about 0.2 mm), the power density created on the fiber end could reach 100 GW/cm^2, which is far above the surface damage threshold of all available materials. This means that such system is infeasible and less demanding solution has to be found. The standard way to reduce the required power density is to reduce energy necessary to produce the flyer. Since speed of the flyer cannot be reduced, the only way to achieve this is to reduce its mass and to increase efficiency of the energy delivering system. The coupling efficiency can be increased by proper design of the detonator. As it was mentioned above, 50% efficiency had been achieved using multilayer design with absorbing material separated from the flyer by strong dielectric layer. High quality optical fibers with negligible losses and efficient coupling of the laser light into fiber allow for additional reduction of the required power. Finally, reduction of the flyer's thickness from several tens of micrometers to two micrometers will reduce required energy by one order of magnitude. With all these methods required power density on entry side of the fiber can be reduced to below 10 GW/cm^2 which can be accepted by some extra resistant materials as fused silica, for example. While such strongly reduced power density can be insufficient to create the flyer energetic enough to initiate detonation in some explosives, it may still cause surface damage of the entry fiber end, especially when this end is not properly cleaned or has some surface defect. This may strongly affect reliability of such detonator and to improve this, the better means to deliver more energy to the flyer are required. Such means can be realized using existing difference between surface and bulk power density damage threshold in high quality optical materials. It is known that the bulk threshold is usually significantly higher than surface one. This property of optical materials can be used in two step laser system. The first step would consist of less powerful laser generator producing light pulse with proper temporary characteristics but with energy insufficient to damage any of following optical components under normal working conditions. The

produced laser power has to be small enough to allow its coupling into amplifying optical fiber without the damage of its entry surface. Once the pulse is coupled into fiber it can be amplified to much higher level without danger of serious damage of the internal part of the fiber. For further reduction of damage possibility of other optical elements the same fiber could be also used to deliver the optical power to the detonator. This imposes additional requirements to the fiber including high volume damage threshold and low losses of laser light even in these parts of the fiber which are not pumped strongly enough. The last condition is automatically fulfilled in so-called four-level laser materials like Nd:YAG or Nd:glass. Because of amorphous structure, the last material is particularly useful for production of optic fiber laser amplifier. This immediately implies that also laser generator should be made of Nd:glass to secure a good match of amplifying bands of laser generator and fiber optic laser amplifier.

As it was mentioned before, required power density in a plane of the absorbing layer of a flyer detonator is actually higher than power damage threshold for majority of optical materials, thus, carried power density in fiber optic core cannot be much higher than that value. This means that core cross section of optical fiber cannot be significantly lower than surface of required flyer and fibers with large core can be used only for delivery of required energy to the slapper detonator. It is known that it is physically impossible to excite the basic mode only in such fibers, thus, multimode light structure can be expected on exit end of the fibers. Experiments demonstrated, however, that when number of modes in fibers is significantly large, as expected for fibers of 0.2 mm in diameter, mode structure does not affect the performance of the laser initiated detonator. For simplicity and to avoid additional losses the detonator is usually created directly on the fiber optic end. If detonator is created separately, some additional needs will be required to refocus laser light leaving the fiber on the absorbing layer of the optically initiated slapper detonator. In this case, if numerical aperture of the fiber is small enough, the fiber of larger diameter can be used for energy

delivery. The delivered energy can be refocused on surface of the absorbing layer creating required power density substantially larger than on exit end of the fiber. This allows for additional reduction of the power density inside the fiber and on the surface of the fiber's facet.

In a multiple points detonator the laser beam produced by laser generator has to be divided into suitable number of the separate beams predestined for initiation of the detonations in corresponding number of points, coupled into separate fiber optic amplifiers, also used for energy delivery to particular detonator. It is obvious that the laser energy produced by generator in this case has to be proportionally higher to secure sufficient energy entering each fiber-optic amplifier. The propagation speed of light in the fibers of the same construction is usually preserved very well even over long distances and can be measured precisely. Hence, very precise control of time delay from the moment when laser pulse is generated to the moment when detonator is activated is possible by simple adjustment of the length of the fiber. This can be used for very precise control of activation sequence in multiple point detonators.

As it follows from the above, in the case of multiple point detonator it is important to divide the laser pulse produced by generator into number of beams equal to the number of required detonation points. For a few points it probably can be done with traditional beamsplitters, for larger number, however, more sophisticated methods have to be applied. It seems that three methods should be taken into considerations: simultaneous illumination of the ends of the densely packed fibers into a single bundle, division of the laser beam into suitable number of separate beams with a diffractive optical elements like Dammann grating, or division of the beam with fiber optic or integrated optic decouplers. Advantages of the first solution are technical simplicity and low sensitivity to misalignment. Its major disadvantages are large losses of light, possible damage of fiber's facets and variations of the coupled energy from fiber to fiber because of Gaussian intensity profile of

laser beam. The variations can be reduced, however, by magnification of beam diameter for price of larger power loses. In this respect Dammann grating approach can be more efficient and may secure very good energy repeatability from fiber to fiber. It also can handle higher power density. The main disadvantage of the solution is necessity to couple each beam separately into fibers, but taking into account relatively large core diameter it should not create significant technical problems. Finally, the third solution is division of light beam using fiber optic or integrated optic power dividers. There are at least three important disadvantages of this solution which include necessity of coupling high power laser pulse into a single fiber, technical difficulties related to creation of power dividers for multimode fibers and large power losses in such dividers. Waveguide power divider with much larger losses, which was never tested in high power applications, can be considered as another version of the above solution, with rather marginal practical value.

Energetic efficiency of the whole system is an extremely important issue since this defined necessary electrical power and size of the required power supply. The efficiency of the previously mentioned Nd:YAG and Nd:glass lasers can be as high as several percent (over 10% energetic efficiency was reported), which means that several Joules of electrical energy may be sufficient to generate enough optical energy for flyer launch. Typically these materials can store well over one Joule of the energy per cubic centimeter, which means that to generate 0.1 J of the energy, a relatively small laser rod pumped by a small light source should be adequate. This makes possible construction of a very compact laser head with short resonator enabling generation of a short laser pulse by means of sufficiently fast Q-switch modulator. Such laser, if properly designed, should be able to deliver required energy in a few to 10 nanoseconds, generating pulses with power in range of 10-35 MW for a single point detonation and proportionally higher for multiple point system.

If concentrated on the surface of optical fiber such power will create power density close to 33-100 GW/cm^2 which is almost by 2 orders of magnitude higher than surface damage threshold of the majority of optical materials, but can be carried out inside the high quality optical materials. This means that energy coupled into fiber have to be reduced by about 33-100 times and amplified the same number of times inside the amplifying fiber. To obtain this the fiber should deliver practically all required energy (30-100 mJ). This amount of energy can be delivered by about 0.1 cm^3 of active material, thus three meters of fiber with core diameter 0.2 mm should be able to provide the required energy if properly pumped.

Once required energy is achieved, there are two ways to use it for slapper launch: to focus it on absorbing surface of the flyer detonator as in earlier described experiment with direct laser launched slapper or to produce the absorbing layer and flyer plate structure directly on the end of the optical fiber. The first approach has several disadvantages, among which there is possible damage of the exit fiber end before all laser energy is released and complexity of the system requiring of focusing lenses, additional mechanical mounting elements and so on. The second solution, undoubtly more technologically demanding, solves majority of these problems automatically.

9. IDENTIFICATION OF INITIAL EXPERIMENTAL TECHNIQUES FOR PLATE LAUNCH

The analysis presented above leads to conclusion that even if direct laser initiation of detonation may have some advantages, it seems that the fiber optic solution only may justify application of optical technology in this field for several important reasons:

- increased resistance to electromagnetic interference,
- improved synchronization for multipoint detonation,
- possible delivery of light energy along bent paths,
- detonator integrated with fiber optics delivery system.

It is understandable that future application of such detonators will strongly depend on the reliability of the system under combat condition and its price. Large-scale production can undoubtly substantially contribute to price reduction, nevertheless standard technology applied in present day laser technique would still result in very high production costs. In this situation it is extremely important to design the system with acceptably low price.

An important feature of the detonator which can be exploited to reduce the price consists in that detonator is a device of a single use. This means that only once during its whole life the detonator should demonstrate complete reliability in performing its duty. After the duty is completed, the resulting explosion will anyway destroy the laser and detonator. It is clear that under such circumstances the whole system should be build for this single act and could be done of elements able to perform their duty only once in life before being destroyed either in course of their action or afterwards by the explosion. In this situation there is no need for building of the system consisting of the multiple use elements as in standard laser technology, thus reliability problem has to be completely redefined and detonator has to be build using criteria different from that applied in normal laser industry. It is

understandable, however, that this approach is not suitable for preliminary research when many experiments have to be completed, to obtain all information necessary for development of the system. The above considerations lead to conclusions that the whole project should consist of two parallel processes:

- research and development study conducted with reliable laser system allowing extraction of all information necessary for development of a single use laser initiated slapper detonator;
- development of the detonator itself in a form of a single use device made of reliable but also single use elements.

The last condition covers all elements starting from long lasting electric batteries which can be fully exhausted after energy necessary to power and control detonator has been delivered; control electronic, especially triggering device, which can be destroyed during its action; pulse light source (exploding wire, or chemical flash lamp, for example) able to deliver required light energy for a single laser pulse in a single outburst act; laser rod and all optical elements which can be destroyed after required laser energy has been generated; optical fiber, whose end can be destroyed after energy has been delivered to slapper detonator and so on. Such approach may significantly reduce technical requirements related to used elements, automatically reducing their contribution to the cost of the device.

While the above approach can lead to significant cost savings when applied in a single use device, it would be extremely costly while utilized for research and development. Thus, a separate laser system is required for performing R&D tasks. The system should include Nd:glass laser with an active road made of the same material like that to produce the core of the fiber optic amplifier. The laser should be able to generate laser pulses of variable length in range from a few to several tenths of nanoseconds. This laser together with all required optics would be used for research on laser

launched flyer plate, to test all factors important for efficient launching of the flyer. These factors should include:

- selection of proper absorbing material and optimization of the thickness of the absorbing layer;
- testing of performance of detonator in function of the spatial distribution of laser energy in laser spot on the surface of the absorbing layer;
- design of the flyer detonator: testing of various constructions and selection of the materials for intermediate dielectric layer and flyer itself;
- optimization of pulse duration and energy;
- shape and speed measurements of the generated flyer;
- behavior of the flyer in flight;
- testing of the detonation development under various initiation conditions (in function of flyer speed, shape and flying distance).

10. SELECTION OF SUITABLE DIAGNOSTIC TECHNIQUES FOR PLATE LAUNCH

To be able to make any conclusions from conducted research, testing of the quality of the generated flyer and mathematical modelling of the process are equally important, thus suitable mathematical tools and diagnostic techniques are necessary. It seems that full modelling of the flyer launch process would be extremely difficult and National Optics Institute does not possess necessary capabilities to perform this task. Fortunately there exists strong and experienced team of specialists at INRS-Énergie et Matériaux (Varennes) which already has gained significant knowledge in mathematical modelling of the interaction of high power density laser radiation with solid targets. INRS-Énergie et Matériaux also possess a unique in Canada laser, able to produce 1 J of energy in time from 500 fs to 600 ps (corresponding

power 2.0×10^{12} W and 1.7×10^{9} W) which can be focused into spot less than 1 mm in diameter. This laser can be used for scientific part of the project which should cover study of applicability of the ultrashort laser pulses for generation of the flyer plate. It is unlikely, however, that for practical reasons such laser would be applicable for production of the detonator, but experimental research obtained with application of such laser should provide additional information necessary for better understanding of interaction of high power laser pulse with solid targets, important for optimization of detonator design, and for verification of numerical modelling of the process. To profit from both their theoretical knowledge and the unique laser facility the related part of research to has to be subcontracted to INRS.

For full understanding of the process it is necessary to develop suitable diagnostic methodology. This should cover measurement speed and shape of the flyer, coupling of the energy from flyer into target and development of the detonation in the explosive. Analysis of techniques applicable for shape diagnostic of the flyer plate is given in the report [53] prepared for DREV earlier by some members of the present team. Because of numerous limitations of earlier known techniques, National Optics Institute has developed a unique holographic system for shape registration of flying plate. The system has been described in detail in report presented to DREV [54] and presently is available from NOI. The system can be used for diagnostic of flyer shape in flight and for study of the interaction of the flyer with transparent targets. We believe that after some modifications of the laser to obtain double-pulse operation it also can be used for analysis of deformation of the flyer during flight, thus it will be able to provide information not available from any other system described in the literature.

Because of an exceptional image depth, the above system can also be used for measurement of the position of the flyer relatively to the background at the moment when the hologram is taken. In association with temporal information available from electronic measurements it can be used for

estimation of the averaged speed of the flyer. However, more sophisticated measurement system will be necessary for detailed measurements of flyer's speed and in this situation we propose development of interferometric system either with optical or electronic registration of the interference field. Proper interferometric system with suitable electronic can be either purchased in USA or developed in Canada. We believe that a newly developed system could be most advanced than those presently available on the market, thus it might become a valued high-tech market product. The electronic part of the system either can also be developed in Canada or purchased in USA. Furthermore, if optical registration method has to be used, the streak camera presently available from INRS can be adopted for these needs.

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12. FIGURES

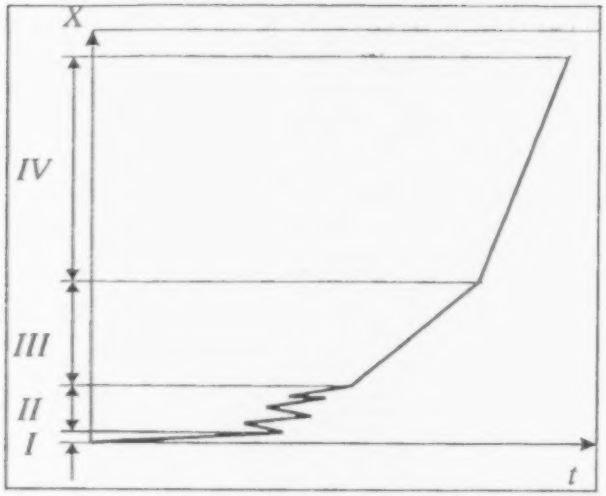


Figure 1 Diagram of transition stages from deflagration to detonation of solid explosives.

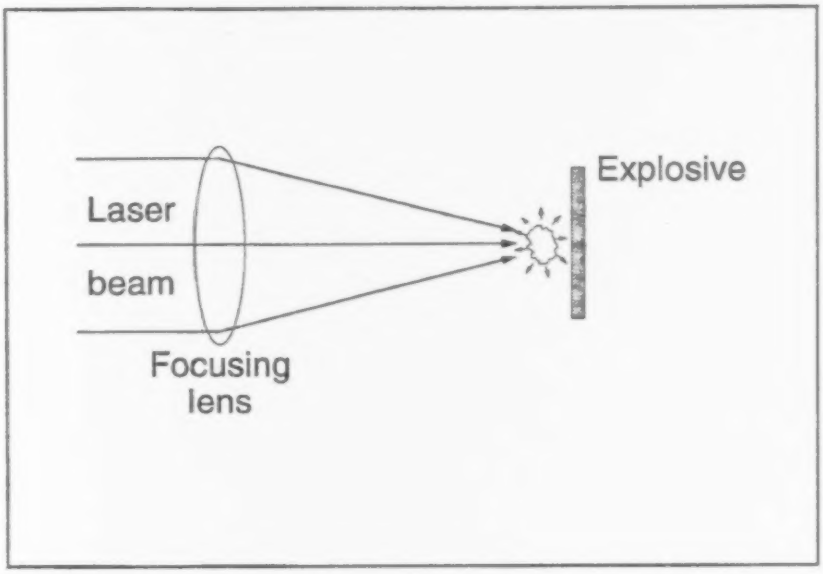


Figure 2 Direct initiation of insensitive explosives.

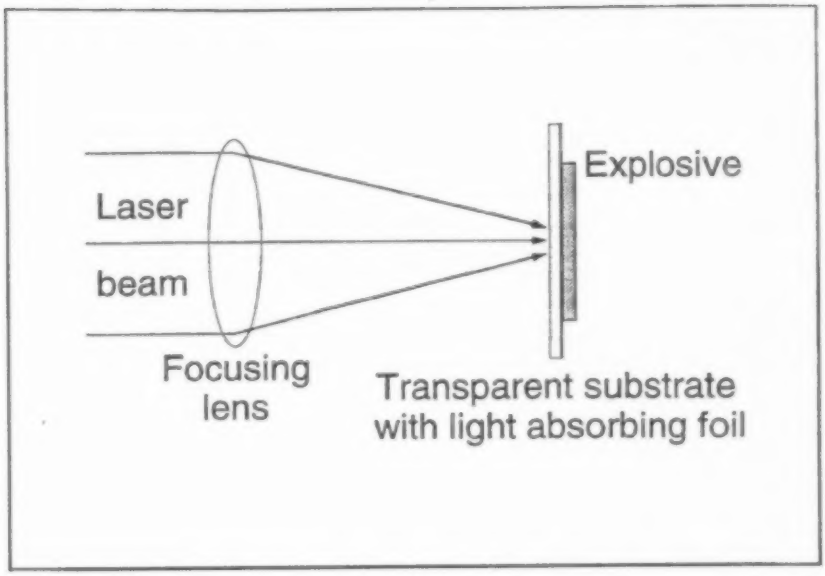


Figure 3 Genenation of shock wave.

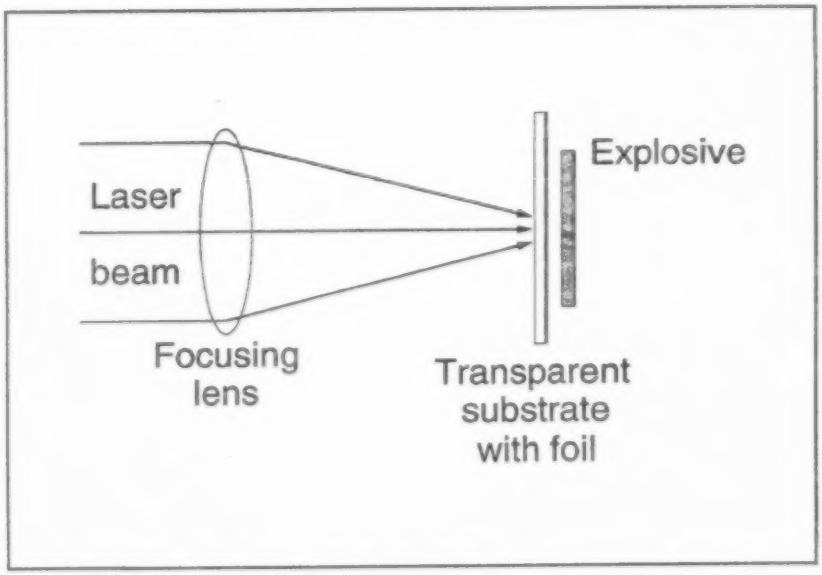


Figure 4 Laser generation of flyer.

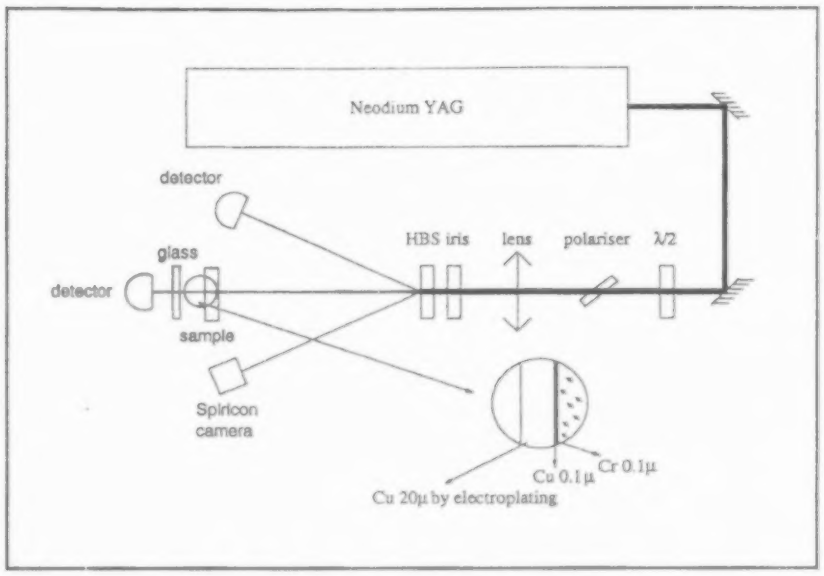


Figure 5 Optical set-up used to generate slapper from a multilayer flyer plate.

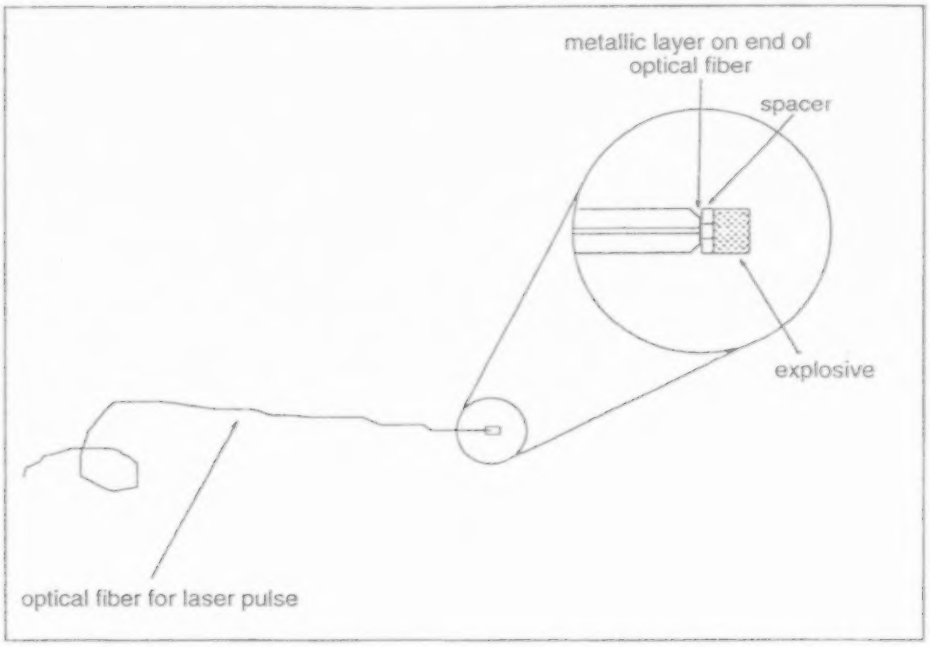
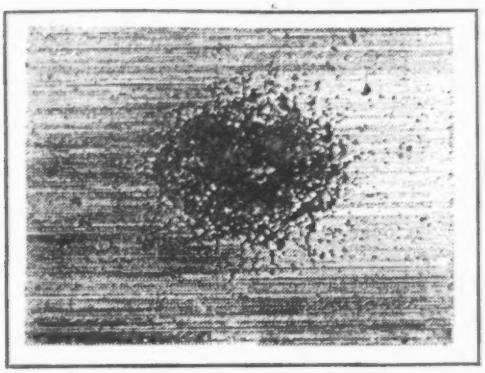
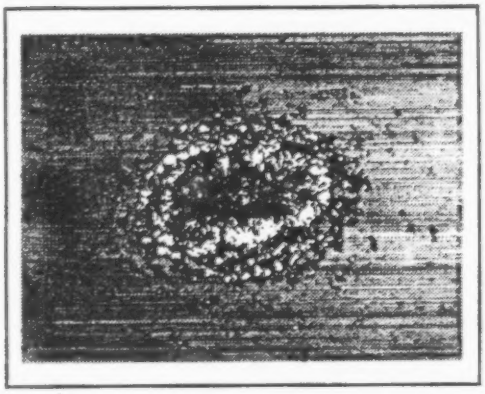


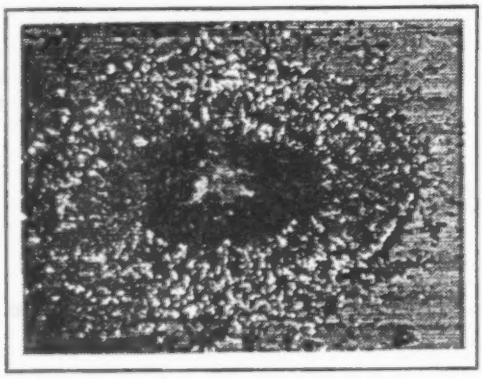
Figure 6 Schematic diagram of an optical fiber detonator and a multipoint initiation system.



a) 20X Magnification



b) 20X Magnification



c) 40X Magnification

Figure 7: Pictures of the remains of three different slappers on microscope slides.

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TITLE:(U) PRELIMINARY STUDY ON LASER-DRIVEN FLYER-PLATE GENERATION FOR SHOCK INITIATION OF SECONDARY EXPLOSIVES

PERSONAL AUTHOR: Pawluczyk, R.; Nappert, L.; Chandonnet, A.; Bernard, P.; Painchaud, Y.; and others

CORPORATE AUTHOR: Defence Research Establishment Valcartier, Valcartier QUE (CAN);National Optics Inst, Ste-Foy QUE (CAN)

ABSTRACT: (U) The three laser initiation approaches are reviewed in this report but the emphasis is put on the laser-driven flyer plate technique. For the latter technique, it is concluded that there does not exist presently sufficient theoretical and experimental data to allow selection of the optimum design parameters of the laser detonator. Among the various experimental data, many were obtained under different and often incomparable conditions such that further extensive, targeted studies are still necessary to produce a suitable HE laser detonator. The report proposes a research plan on laser-driven flyer plates combining mathematical modeling with experimental work for studying all factors important to the efficient launching of the flyer plate. It also identifies the diagnostic techniques necessary to obtain a full understanding of the launching process. The research contract provides DREV with a knowledge of the state of the art in laser initiation of HE materials. The proposed research plan gives the information that will allow DREV to decide whether or not to invest resources in laser initiaiton of HE materials.

DESCRIPTORS: (U) Pyrotechnics;Explosives;Experimentation;Shock waves;Detonation;Lasers;Ignition;Plates;Experimental data

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Important Notices